Microstructural Modification and Resultant Properties of Friction Stir Processed Cast NiAl Bronze

Murray W. Mahoney[1], William H. Bingel[1], and Rajiv S. Mishra[2]

[1]Rockwell Scientific, 1049 Camino Dos Rios, Thousand Oaks, CA 91360 USA

mmahoney@rwsc.com & wbingel@rwsc.com

[2]Department of Metallurgical Engineering, University of Missouri, Rolla, MO 65401, USA

rsmishra@umr.edu

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Abstract

Friction stir processing (FSP) is being developed as a metal working tool to heal casting defects and modify microstructures in a cast NiAl bronze (NAB) alloy for the purpose of substantially increasing mechanical properties. The initial microstructural evolution and resultant mechanical properties for the variety of microstructures created by FSP are reported herein. The dominant microstructural morphologies created by FSP include Widmanstätten, equiaxed fine grain, and a banded or lamellar structure. These microstructures exist concurrently within the FSP zone at different locations and with different volume ratios. The mechanical properties of these different microstructures are established using a micro-tensile test procedure. In addition, bulk mechanical properties are presented to illustrate mechanical properties of the composite microstructure and the Widmanstätten microstructure as a single morphology.

Introduction

Friction stir processing (FSP) is evolving as a new local thermomechanical processing tool to tailor the microstructure in metals for specific applications. For example, FSP has been demonstrated to create high strain rate superplasticity in thick section (5 mm) aluminum alloys [1], enhance formability to accommodate bending in very thick (25 mm) aluminum plate [2], heal casting defects and increase ductility in cast aluminum alloys [3], heal casting defects and improve corrosion resistance in a cast Mn-Cu alloy [4], homogenize and refine the microstructure in a powder metallurgy aluminum to increase ductility [5], and modify fusion welds in both iron and aluminum base alloys to improve mechanical properties [6,7]. FSP, with modifications to both tool design and process parameters, uses the methodology developed for friction stir welding (FSW) [8], but with no joining. Instead of joining, FSP is applied to a metal’s surface to heat, deform, and reforge the affected volume, i.e., thermomechanically process a selected volume to tailor the local microstructure and thus improve specific properties. This study develops FSP procedures with objectives to significantly increase the mechanical, corrosion, and fatigue properties of cast NiAl bronze (NAB). This manuscript reports results for the microstructural evolution associated with FSP of NAB and the resultant mechanical properties. Work to establish additional properties for these same microstructures is in progress.

Experimental Procedure

The NAB alloy selected for this study was a copper-base quaternary of composition 9.1Al-4.4Ni-3.9Fe-1.2Mn-0.14Zn-Cu balance (wt %). A summary of the microstructural development in NAB can be found in ref. [9] and a detailed discussion of the effect of FSP on the microstructure of as-cast NAB can be found in another manuscript published within these proceedings [10]. Thus, within this manuscript, the microstructural evolution associated with FSP will be limited to optical microscopy. Friction stir processing procedures have been presented in detail elsewhere. [1] Briefly, a nonconsumable tool, with a protruding pin beneath a larger diameter shoulder, is inserted into the work-piece, rotated at a predetermined rate, and moved in a lateral, rotational, or rastering motion to thermomechanically process the prescribed volume of metal. The tool pin establishes both the penetration depth, and in concert with FSP parameters and shoulder design, the mixing pattern. During FSP of NAB, temperatures approach the solidus and as such tool materials need to maintain shape, oxidation resistance, and wear resistance at a temperature of at least 1000ºC. A number of tool materials meet these criteria. However, at this time, as with the FSP parameters, these data are proprietary. To evaluate the effect of FSP on the mechanical properties of cast NAB, mini tensile specimens of 1.3 mm gage length and 1.0 mm gage width were electro-discharge machined in the transverse direction from the FSP region, i.e., oriented in the long transverse direction in the plate or normal to the tool rotation axis. These specimens were subsequently ground and polished to a final thickness of ~0.5 mm. Tensile tests were conducted at room temperature using a computer-controlled, custom-built mini tensile tester with an initial strain rate of 1×10^{-3} s^{-1}. Bulk tensile properties were determined by machining round tensile bars along the processed zone axis that included only processed material. The gage diameter was either 3 or 6 mm. These test bars contain either a single microstructure or a composite of the microstructures created by FSP.

Results and Discussion

Microstructural Evolution. The three dominant microstructures created in NAB by FSP are illustrated in Figs. 1a-1c and are in sharp contrast to the coarse as-cast NAB microstructure illustrated in Fig. 1d. Details of these FSP microstructures, including orientation imaging analysis, transmission electron microscopy, and discussions of the microstructural and second phase evolution, are presented elsewhere within these proceedings. [10] Accordingly, herein we will present only a macro description sufficient to correlate with mechanical properties. Figure 1a illustrates a lamellar or banded microstructure. The bands consist of α (white areas), and martensite containing Widmanstätten α (dark areas). [10] The bands are elongated in a horizontal direction, perpendicular to the tool rotation axis. Figure 1b illustrates a recrystallized, equiaxed fine grain microstructure likely with the same phases present as with the lamellar structure but as discreet grains as opposed to the bands. However, this microstructure also shows a phase orientation bias in the horizontal direction. Figure 1c illustrates a Widmanstätten or basket weave microstructure. There does not appear to be any macro orientation bias with the Widmanstätten microstructure. For all mini tensile samples, the tensile axis was taken horizontal to the micrographs in Fig. 1, i.e., micro tensile samples were oriented in the long traverse direction in the FSP plate or normal to the axis of the FSP tool. There may be anisotropy in properties associated with the lamellar and fine grain microstructures. However, additional mechanical testing would be required with the specimen axis normal to the plate surface to evaluate this hypothesis.

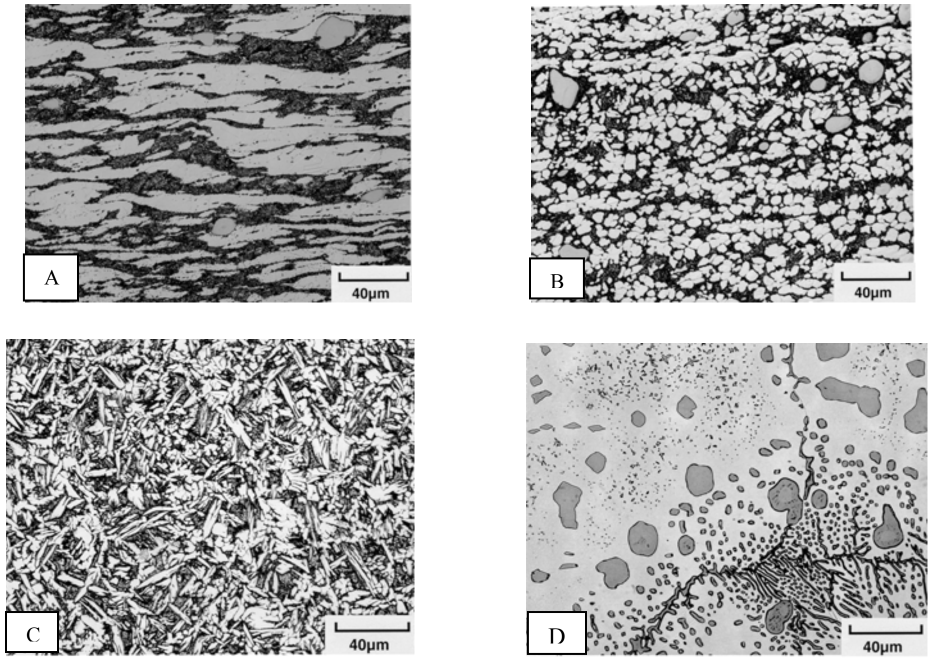

Figure 1 Microstructures created in NiAl bronze by friction stir processing. a) Lamellar, b) fine grain, and c) Widmanstätten, d) as-cast.

Mechanical Properties. Table 1 tabulates hardness and mechanical property results for the different FSP microstructures created in NAB. These results are from both the mini-tensile samples and from larger bulk samples. As-cast results are for an average of six samples using round-bar tensile samples of diameter 3 mm. Due to the casting defects and significant chemical segregation in the as-cast NAB, it is difficult to obtain consistent results with the small gage section used for the mini-tensile tests. However, even with different test sample geometries, a comparison between as-cast and FSP results represents real property differences. For example, as shown below, test results are equivalent for both the mini and bulk test sample geometries for the FSP Widmanstätten microstructure (compare lines C and F in Table 1).

Table 1 Hardness and mechanical properties for friction stir processed NiAl bronze.

[1]Line	Microstructure NiAl Bronze	Hardness R_B	Elongation (%)	Yield Strength (MPa)	Tensile Strength (MPa)
A	Lamellar	92	----	480	756
B	Fine Grain	91	23	508	776
C	Widmanstätten	93	20	572	823
D	As-Cast	68-75	20	214	445
E	Composite of All Microstructure	X	23	433	741
F	Widmanstätten	93	24	591	824

[1] Lines A, B, and C are properties developed with mini-tensile samples with gage area 0.5 mm^2. Lines D, E, and F are properties developed with 3 and 6 mm diameter tensile bars. Lines A, B, and C illustrate properties in the long transverse direction for individual microstructures. Line D illustrates properties for the as-cast NiAl bronze. Line E illustrates properties for a composite of the three microstructures. Line F illustrates properties for the Widmanstätten microstructure for a large cross section.

Hardness results illustrate a significant difference between the as cast and FSP microstructures (RB hardness 71 vs. 92) but do not differentiate between the different FSP microstructures. This result is not surprising. With the refined microstructures and the number of phases present in each microstructural morphology, even micro-hardness hardness results are likely measuring hardness in a composite of phases.

In all cases, elongation is high. The average elongation to failure for the as-cast NAB was 20%; albeit, due to casting defects and the inhomogeneous microstructure, the ductility at times can be significantly lower. Following FSP, the strain to failure remains high and as shown in Table 1, for some microstructures even increases. This is especially true for the larger diameter samples where elongation was consistently greater than 23%. For the apparent banded microstructures, i.e., lamellar and fine grain, ductility results could be different if testing was performed normal to the banding.

Yield and tensile strengths for the as-cast NAB are 214 MPa and 445 MPa respectively. In comparison, following FSP and for the mini-tensile samples, lines A and B, table 1, yield strength more than doubles and tensile strength increases from 70% to 85% for the lamellar and fine grain microstructures. Strengths for the lamellar and fine grain microstructures are similar. We speculate that these results reflect the apparent banding of the fine α-grains and perhaps with more mixing during FSP, strength could increase even more with the fine grain microstructure. Mechanical properties of the Widmanstätten microstructure are the highest for the mini-tensile sample; line C, table 1. Yield strength increases by a factor of 1.7 and tensile strength increases by 85%. These dramatic property increases reflect the fine homogeneous microstructure and the absence of casting porosity following friction stir processing.

As shown in the macrograph in Fig. 2, a composite of microstructures can be created by FSP. Round tensile bars were machined to include all the microstructures in the gage diameter, i.e., lamellar, fine grain, and Widmanstätten. For a range of processing parameters and tool geometries, average elongation for twelve samples was high at 23%, yield strength was 433 MPa, and tensile strength 741 MPa; line E, table 1. This is a significant increase over the as-cast NAB, but mechanical properties are less than that demonstrated for the single Widmanstätten microstructure using a mini-tensile sample; line C, table 1. This illustrates the influence of the "weaker" microstructures on mechanical properties. Thus, to maximize strength it would be preferable to create a single, homogeneous Widmanstätten microstructure. Figure 3 illustrates a 27 mm deep FSP zone created with two passes where a homogeneous Widmanstätten microstructure was created. The corresponding properties for this sample include a strain to failure of 24%, yield strength of 591 MPa, and a tensile strength of 824 MPa, line F, table 1. These results are essentially equivalent to the mechanical properties demonstrated with the mini tensile samples for this same microstructure.

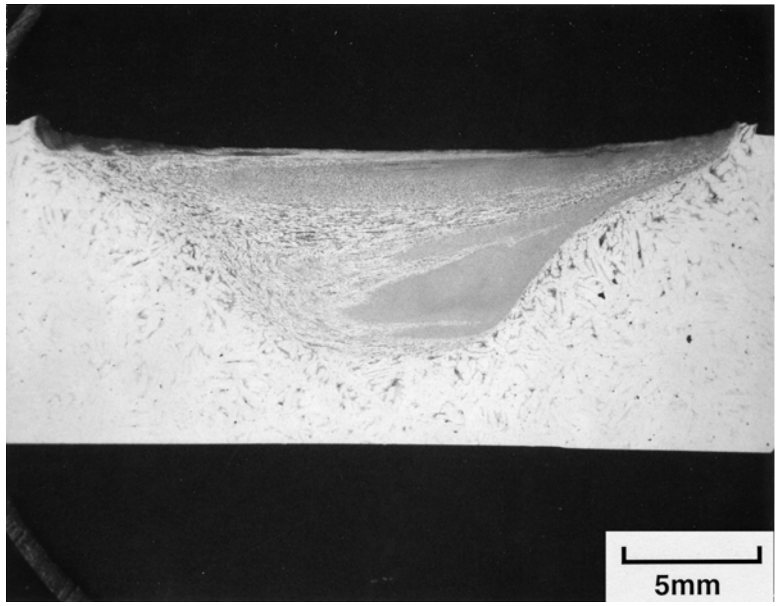

Figure 2 Friction stir processed zone in NiAl bronze with a composite of microstructures.

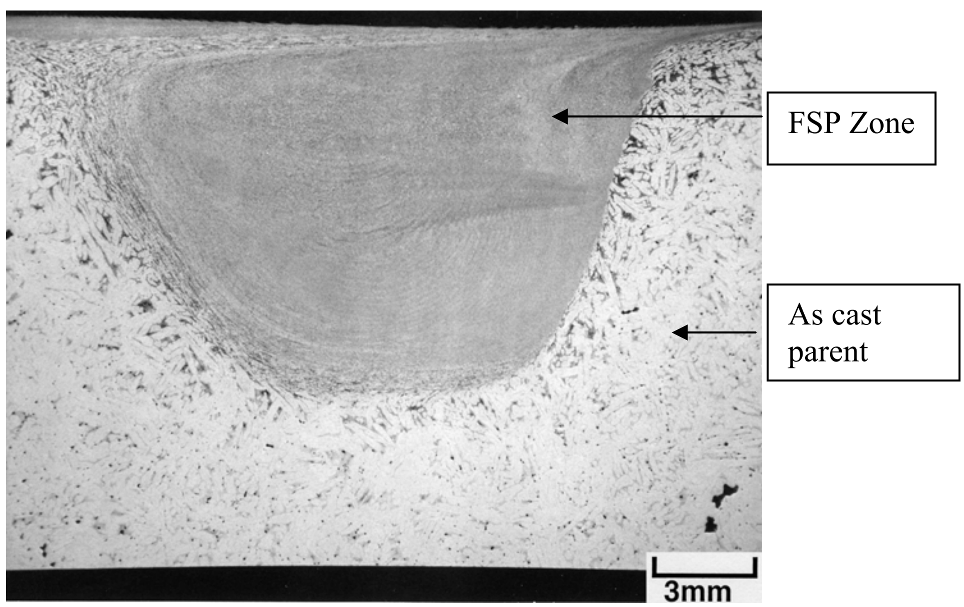

Figure 3 Friction stir processed zone in NiAl bronze with a homogeneous Widmanstätten microstructure.

Conclusions

This work has demonstrated that friction stir processing (FSP) can create a variety of microstructures in cast NiAl bronze. These microstructures include lamellar, fine grain, and Widmanstätten. Either a composite of microstructures, including all three, or a single Widmanstätten microstructure can be created by FSP. All FSP microstructures have significantly superior mechanical properties compared to the as-cast microstructure. This is due to the elimination of casting defects and refinement of the microstructure by friction stir processing. When the test sample contained a composite of the microstructures, the mechanical properties were dictated by the weakest microstructure, albeit, still considerably superior to the as-cast microstructure. The greatest property increase was achieved when the microstructural morphology was entirely Widmanstätten. When the microstructure in the gage section was entirely Widmanstätten, increases in yield strength of 170% and tensile strength of 85% were realized. Also, ductility in the Widmanstätten microstructure was equivalent to or better than for the cast alloy.

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